DC, RF, and Microwave Noise Performances of AlGaN/GaN HEMTs on Sapphire Substrates

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***Abstract*—High-performance AlGaN/GaN high electron-mobility transistors with 0.18-μm gate length have been fabricated on a sapphire substrate. The devices exhibited an extrinsic transconductance of 212 mS/mm, a unity current gain cutoff frequency (f_T) of 101 GHz, and a maximum oscillation frequency $(f_{\rm MAX})$ of 140 GHz. At $V_{\rm ds} = 4$ V and $I_{\rm ds} = 39.4$ mA/mm, the devices exhibited a minimum noise figure $({\rm NF}_{\rm min})$ of 0.48 dB and an associated gain (G_a) of 11.16 dB at 12 GHz. Also, at a fixed drain bias of 4 V with the drain current swept, the lowest ${\rm NF}_{\rm min}$ of 0.48 dB at 12 GHz was obtained at $I_{\rm ds} = 40$ mA/mm, and a peak G_a of 11.71 dB at 12 GHz was obtained at $I_{\rm ds} = 60$ mA/mm. With the drain current held at 40 mA/mm and drain bias swept, the ${\rm NF}_{\rm min}$ increased almost linearly with the increase of drain bias. Meanwhile, the G_a values decreased linearly with the increase of drain bias. At a fixed bias condition ($V_{\rm ds} = 4$ V and $I_{\rm ds} = 40$ mA/mm), the ${\rm NF}_{\rm min}$ values at 12 GHz increased from 0.32 dB at -55 °C to 2.78 dB at 200 °C. To our knowledge, these data represent the highest f_T and $f_{\rm MAX}$, and the best microwave noise performance of any GaN-based FETs on sapphire substrates ever reported.**

***Index Terms*—GaN, AlGaN, HEMT, microwave noise.**

I. INTRODUCTION

AlGaN/GaN high electron-mobility transistors (HEMTs) have demonstrated device characteristics, which make them excellent candidates for high-power, high-frequency, and high-temperature applications because of unique material properties. State-of-the-art results of AlGaN/GaN HEMTs include a breakdown voltage of as high as 570 with a source–drain spacing of 13 μm, a gate length of 0.5 μm using an overlapping gate structure [1], a unity current gain cutoff frequency (f_T) of 101 GHz, a maximum oscillation frequency $(f_{\rm MAX})$ of 155 GHz for a 0.12-μm device [2], and an f_T of 110 GHz for a 50-nm device [3], together with a power density of 9.1 W/mm at 8 GHz [4], as well as a total output of 40.7 W for a 12-mm-wide AlGaN/GaN transistor on SiC at 10 GHz [5]. Up to now, extensive investigations have been conducted on the potential of AlGaN/GaN HEMTs for power applications [6]–[9]. Investigations on microwave noise performances of GaN-based devices are of importance because the possibility of applications of these devices in low-noise front-end systems would eliminate the need for additional protection circuits with the advantages of high breakdown voltages. Though GaAs- and InP-based HEMTs have demonstrated excellent microwave noise performances, these devices generally suffer from low-breakdown voltages. At present, in front ends of microwave systems such as satellite communications, limiters or protection circuits are required to protect low-noise amplifiers (LNAs) because of low-breakdown voltages of GaAs- and InP-based low-noise HEMTs. Devices like GaN-based HEMTs with low noise figures and high breakdown voltages will remove the front-end protection circuits. Such robust low-noise devices will simplify system designs and the complexity of layer structures and device processing and possibly improve the integration of circuits. However, to date, a limited number of investigations have been reported on microwave noise performance of GaN-based heterojunction field-effect transistors (HFETs). These preliminary investigations have shown that AlGaN/GaN HEMTs on SiC exhibit excellent microwave noise properties that are comparable to those of AlGaAs/GaAs HEMTs. Specifically, 0.25-μm AlGaN/GaN HEMTs with a minimum noise figure $({\rm NF}_{\rm min})$ of 0.77 dB at 5 GHz and an ${\rm NF}_{\rm min}$ of 1.06 dB at 10 GHz were reported [10]. An ${\rm NF}_{\rm min}$ of 0.60 dB at 10 GHz was achieved in an AlGaN/GaN HEMT on SiC with a gate length of 0.15 μm [11]. Recently, we reported AlGaN/GaN HFETs on an insulating SiC substrate with a gate length of 0.12 μm, which exhibited less than 1 dB ${\rm NF}_{\rm min}$ at 18 GHz, indicating a potential for broad-band applications of these devices [2]. All these previous studies concentrated on GaN-based HEMTs on SiC substrates because of less lattice-mismatch problems, hence, better material quality. Progress has been made in the growth of AlGaN/GaN HEMTs on sapphire with resulting excellent two-dimensional electron gas properties. Although sapphire has less desirable heat conduction properties than SiC, it is much cheaper. AlGaN/GaN HEMTs on sapphire are attractive especially for low-noise applications because low-noise operation imposes less severe self-heating problems than power operation does. Therefore, AlGaN/GaN HEMTs could provide cost-effective solutions for analog front-end systems. In this paper, for the first time, we report results on microwave noise characteristics of AlGaN/GaN HEMTs on sapphire substrates in comparison with our recently reported noise characteristics of GaN-based HEMTs on SiC substrates.

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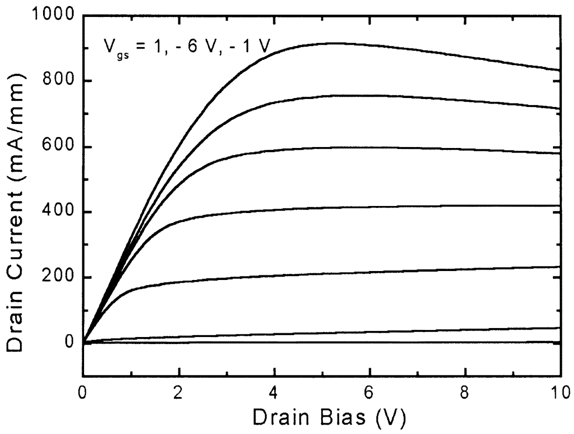

Fig. 1. DC *I–V* characteristics of a 0.18-μm AlGaN/GaN HEMT with a gatewidth of 100 μm. The gate bias was swept from 1 to -5 V in a step of -1 V.

II. Device Layer Structure and Device Processing

The layer used in this study was grown by metal–organic chemical vapor deposition (MOCVD) on sapphire substrates. The epilayer consists of undoped 2-μm GaN and 25-nm $Al_{0.35}Ga_{0.65}N$. Hall measurements showed a sheet carrier concentration of 1.3 $\times$ 10^{13} cm^{-2} and an electron mobility of 1330 cm^2/V at room temperature. The mesa etching was achieved in a Cl_2 plasma by an inductively coupled-plasma reactive ion etcher (ICP RIE). Ohmic contacts were obtained by Ti/Al/Ti/Au evaporation and rapid thermal annealing at 800 °C for 30 s. The ohmic contact resistance is approximately 0.2-Ω·mm. Ni/Au mushroom-shaped gates with a gate length of 0.18 μm, but with a wide (1 μm) T-gate head were fabricated by electron beam lithography. The devices had a gatewidth of 100 μm and a source–drain spacing of 3 μm.

III. DC and RF Performances

On-wafer dc measurements were performed using an HP4142 semiconductor parameter analyzer. Fig. 1 shows the *I–V* characteristics of a typical device. The gate was biased from 1 V to -5 V in a step of -1 V. The devices exhibited high current drive capability and excellent pinchoff characteristics. The maximum drain current was 920 mA/mm at a gate bias of 1 V and a drain bias of 5 V. The device pinched off completely at $V_{\rm gs} = -5$ V with a drain current less than 1 mA/mm at $V_{\rm ds} = 10$ V. At gate biases of 1 and 0 V, current drops were observed starting at $V_{\rm ds} = 5$ V, caused by the self-heating effect because of the poor thermal conductivity of sapphire substrate. The dc transfer characteristics are shown in Fig. 2(a). The drain was biased at 5 V. A peak extrinsic transconductance (g_m) of 212 mS/mm was measured at $V_{\rm gs} = -2.84$ V and $V_{\rm ds} = 5$ V. By defining the threshold voltage $(V_{\rm th})$ as the gate-bias intercept of the extrapolation of $I_{\rm ds}$ at the point of peak g_m, the $V_{\rm th}$ of the device was determined to be -4.4 V. The sub-threshold drain-current characteristics are plotted in logarithmic scale against gate bias in Fig. 2(b). The drain was biased at 5 V for this measurement. A sub-threshold slope of 52.9 mV/decade and low off-state current (approximately 1 nA), shown in Fig. 2(b), were achieved, which indicated good gate control of carriers in the channel region. Fig. 3 shows the gate Schottky diode characteristics. In this

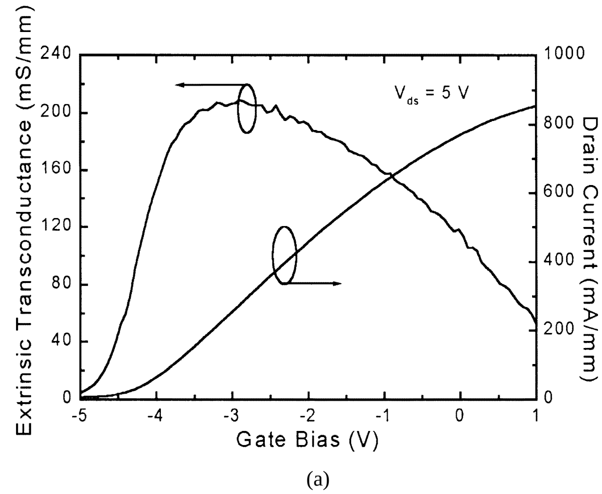

Fig. 2. (a) DC transfer characteristics of the 0.18-μm AlGaN/GaN HEMT with a gatewidth of 100 μm. The drain bias was 5 V. The extrinsic transconductance peaks at $V_{\rm gs} = -2.84$ V with a value of 212 mS/mm. The threshold voltage $(V_{\rm th})$ is determined to be -4.4 V by defining the gate-bias intercept of the extrapolation of $I_{\rm ds}$ at the point of peak extrinsic transconductance. (b) The sub-threshold drain-current characteristics of the 0.18-μm AlGaN/GaN HEMT with a gatewidth of 100 μm. The drain bias was 5 V.

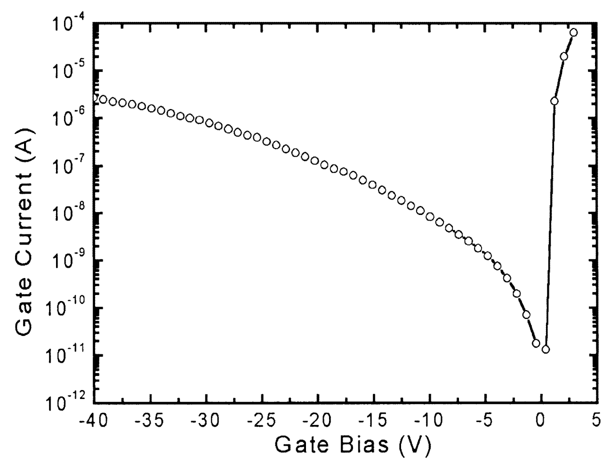

Fig. 3. Gate Schottky diode characteristics of a 0.12-μm AlGaN/GaN HEMT with a gatewidth of 50 μm. In this measurement, the drain was shorted to the source. The turn-on voltage of the diode was determined to be 2.76 V.

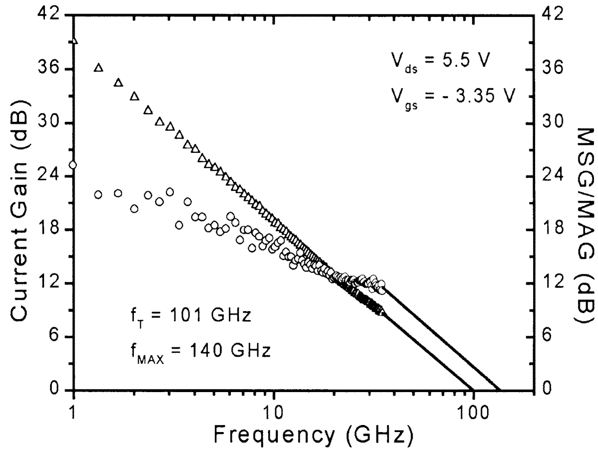

Fig. 4. Measured current gain ($|h_{21}|$) and MSG versus frequency for a typical 0.18-μm AlGaN/GaN HEMT with a gatewidth of 100 μm. The device was biased at $V_{\rm ds} = 5.5$ V and $V_{\rm gs} = -3.3$ V. The unity current gain cutoff frequency (f_T) and maximum oscillation frequency ($f_{\rm MAX}$) were determined to be 100 and 140 GHz, respectively, by extrapolations of -20-dB/decade slopes.

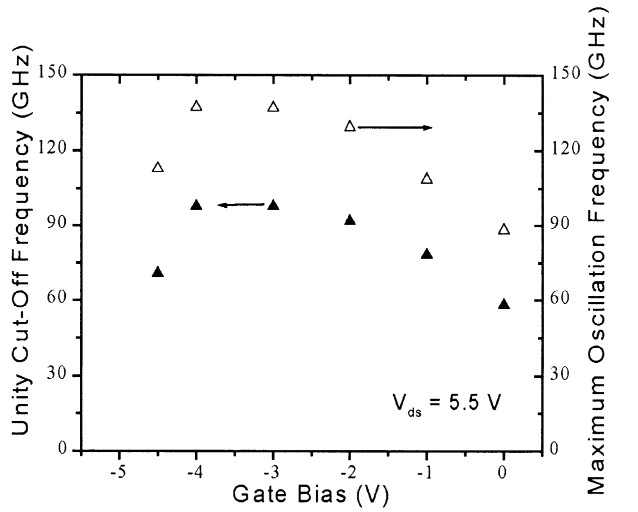

Fig. 5. Measured unity current gain cutoff frequency (f_T) and maximum oscillation frequency ($f_{\rm MAX}$) as a function of gate bias of the 0.18-μm AlGaN/GaN HEMT with a gatewidth of 100 μm. The drain bias was kept at 5.5 V.

measurement, the drain was shorted to the source and gatewidth of the device was 50 μm. A high forward-bias turn-on voltage of 2.76 V was observed at a gate current of 1 mA/mm. Under reverse bias, no soft breakdown was observed up to 40 V where the gate leakage current was as small as 2.6 μA.

For microwave characteristics, on-wafer measurements of S-parameters from 1 to 35 GHz using a Cascade Microtech Probe and an HP8510B Network Analyzer were used to determine f_T and $f_{\rm MAX}$ of the devices. The current gain ($|h_{21}|$) and the maximum stable power gain (MSG) and the maximum available power gain (MAG) data are plotted as a function of frequency in Fig. 4. Since the stable factor (k) was less than 1 up to 35 GHz (not shown in Fig. 4), only the MSG is shown in Fig. 4. f_T and $f_{\rm MAX}$ values were obtained by the extrapolation of $|h_{21}|$ and the MSG using a -20-dB/decade slope. At a drain bias of 5.5 V and a gate bias of -3.3 V, an f_T of 100 GHz and a maximum oscillation frequency of 140 GHz were measured. Since the transistor is potentially unstable at 35 GHz and we simply used a -20-dB/decade slope to determine the $f_{\rm MAX}$, the actual $f_{\rm MAX}$ should be higher than 140 GHz. Nevertheless, to our knowledge, these are the highest data ever reported for any type of GaN FETs on sapphire substrates. The f_T and $f_{\rm MAX}$ values as functions of gate bias for the same transistor are shown in Fig. 5. In these measurements, the drain was biased at 5.5 V, while the gate was biased in the range of -4.5 to 0 V. The drain current obtained was in the range of 14.3 to 770 mA/mm. The f_T values obtained ranged from 58 to 100 GHz, while $f_{\rm MAX}$ values varied from 88 to 137 GHz. The highest f_T and $f_{\rm MAX}$ were measured at the drain current of 180 mA/mm. It should be pointed out that the transistor still exhibited over 55 GHz f_T and over 85 GHz $f_{\rm MAX}$ at $I_{\rm ds} = I_{\rm dss}$, which indicates the potential for high-power capability at high frequencies.

IV. Microwave Noise Characteristics

High-frequency noise performances of the devices were measured using an ATN NP5 noise parameter test set in conjunction with an HP8570B noise-figure meter, an HP8971B noise-figure test set, and an HP8510B Network Analyzer over 2–18-GHz frequency range. Fig. 6(a) shows $\rm NF_{min}$ and G_a as a function of frequency. The straight line in Fig. 6(a) is a linear fit to the minimum noise figures. For these measurements, devices were biased at $V_{\rm ds} = 4$ V and $I_{\rm ds} = 39.4$ mA/mm. Compared to our previous results on 0.25-μm devices [10], the present noise performances improved significantly. An $\rm NF_{min}$ of 0.48 dB and a G_a of 11.16 dB were measured at 12 GHz. In the frequency range of 4–18 GHz, $\rm NF_{min}$ is in the range of 0.25–1.13 dB and G_a ranges from 16.9 to 9 dB. These improvements were not only demonstrated at low frequencies, but also at high frequencies. For nitride-based transistors, the frequencies of interest are currently in the X- and Ku-band ranges. For example, our devices exhibited an $\rm NF_{min}$ of 1.1 dB at 18 GHz, which is comparable to what we achieved on devices on SiC substrates with a gate length of 0.12 μm (1.0-dB $\rm NF_{min}$ at 18 GHz [2]). To our knowledge, these are the best $\rm NF_{min}$ and highest G_a for GaN FETs on sapphire substrates ever reported. The other important noise parameter is the optimum generator admittance, which is often characterized by the reflection coefficient $(\Gamma_{\rm opt})$ at minimum noise figure in measurements. Figs. 6(b) shows the magnitude and angle of the optimum reflection coefficient $\Gamma_{\rm opt}$ versus frequency at the same bias. The magnitude of $\Gamma_{\rm opt}$ is in the range of 0.82–0.89, while the angle increases along with frequency from 3.9° at 4 GHz to 26.1° at 18 GHz. Fig. 6(c) shows the noise resistance against frequency. The noise resistance decreases with frequency from 108 Ω at 4 GHz to approximately 95 Ω at 18 GHz. This is slightly higher than that measured on devices on SiC substrates [2], indicating higher sensitivity on device noise performance.

Fig. 7 shows the dependence of $\rm NF_{min}$ (down triangles) and G_a (up triangles) at 12 GHz on the drain current $I_{\rm ds}$. In these measurements, the drain bias was fixed at 4 V and the gate biases were adjusted to control the drain current. For comparison, recently reported $\rm NF_{min}$ and G_a of devices on SiC with a gate length of 0.12 μm at 12 GHz are also shown in Fig. 7 [2]. These

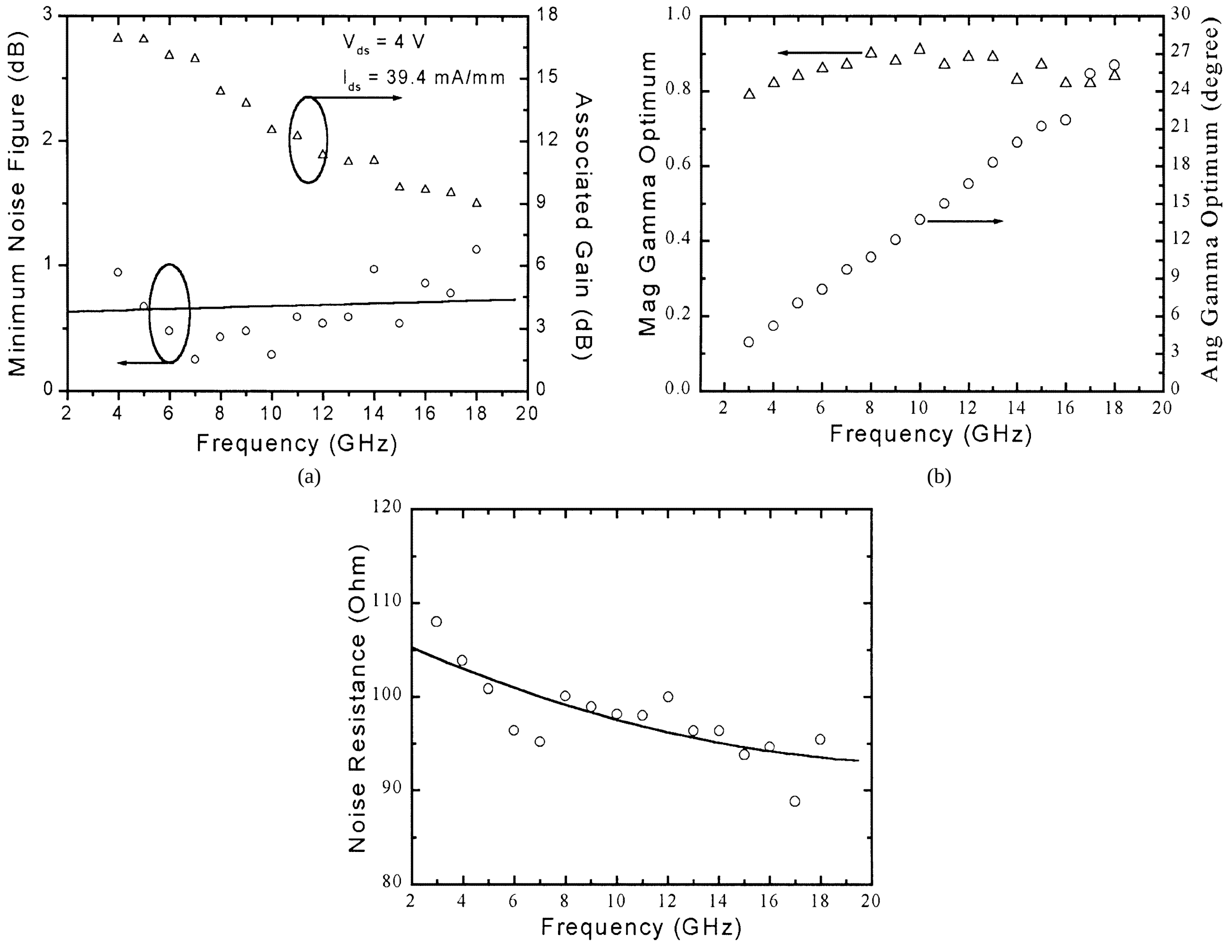

Fig. 6. (a) Minimum noise figure $(\mathrm{NF}_{\min})$ and associated power gain (G_a) versus frequency for the typical 0.18-μm AlGaN/GaN HEMT with a gatewidth of 100 μm. The device was biased at $V_{\mathrm{ds}} = 10$ V and $I_{\mathrm{ds}} = -39.4$ mA/mm. The solid straight line is the linear fit to the measured $\mathrm{NF}_{\min}$. (b) Magnitude and angle of the optimum reflection (Γ_{opt}) versus frequency at the same biases. (c) Noise resistance versus frequency of the device under the same bias.

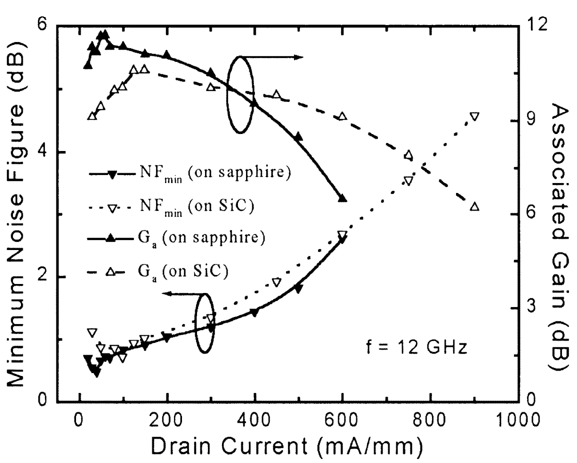

Fig. 7. Minimum noise figure $(\mathrm{NF}_{\min})$ (down triangles) and associated power gain (G_a) (up triangles) at 12 GHz against drain current for the typical 0.18-μm AlGaN/GaN HEMT with a gatewidth of 100 μm. The drain bias was 4 V. $(\mathrm{NF}_{\min})$ and (G_a) of 0.2-μm AlGaN/GaN HEMTs are also shown for comparison.

devices on SiC exhibited an I_{dss} of 985 mA/mm, a peak extrinsic transconductance of 217 mS/mm, an f_T of 101 GHz, and an f_{MAX} of 155 GHz. For the devices on sapphire substrate, the drain-current bias was in the range of 20 to 600 mA/mm. At 20 mA/mm, the $\mathrm{NF}_{\min}$ and G_a were 0.7 and 10.72 dB, respectively. The minimum $\mathrm{NF}_{\min}$ (0.48 dB) was measured at a current of approximately 40 mA/mm, while the current level at which the highest G_a (11.71 dB) was measured was approximately 60 mA/mm. These current values are lower than the drain-current levels of peak G_a and lowest $\mathrm{NF}_{\min}$ in comparison with devices on SiC. For the devices on SiC substrates, the devices exhibited slightly higher $\mathrm{NF}_{\min}$ in the current range of less than 600 mA/mm and slightly lower G_a in the current range of less than 350 mA/mm. However, G_a of devices on sapphire substrate dropped faster with the increase of drain current. Also, at higher current level (>400 mA/mm), $\mathrm{NF}_{\min}$ of devices on sapphire increased much faster than that of devices on SiC. These trends are attributed to the poor heat dissipation ability resulting from the poor thermal conductivity of sapphire substrates. The dependence of $\mathrm{NF}_{\min}$ and G_a on drain bias (V_{ds}) at 12 GHz (up triangles) are plotted in Fig. 8. For comparison, $\mathrm{NF}_{\min}$ and G_a data of devices on SiC are also shown in Fig. 8. In the measurements, the drain current was held at 40 mA/mm for devices on sapphire and 114 mA/mm for devices on SiC. The drain-bias range was from 2 to 15 V for devices on sapphire and from 4 to 16 V for devices on SiC. For the device on the sapphire substrate, the $\mathrm{NF}_{\min}$ reached a minimum value (0.54 dB) at $V_{\mathrm{ds}} = 4$ V. It then increased almost linearly to 2.14 dB

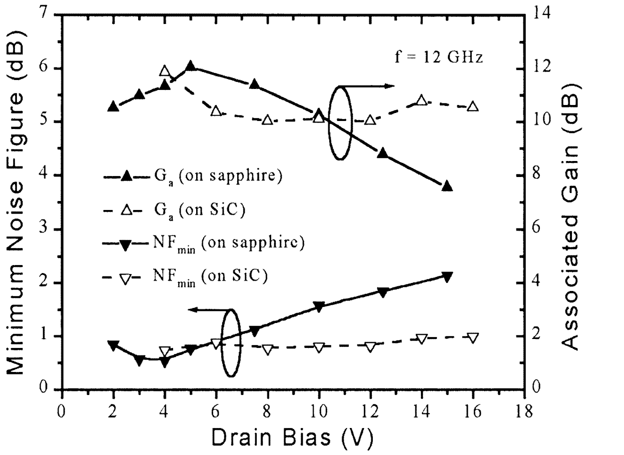

Fig. 8. Minimum noise figure (NF_{min}) and associated power gain (G_a) at 12 GHz (up triangles) as a function of drain bias for the typical 0.18-μm AlGaN/GaN HEMT with a gatewidth of 100 μm. NF_{min} and G_a data of 0.12-μm AlGaN/GaN HEMTs on SiC are also shown for comparison. The drain current was held at 40 mA/mm for the device on sapphire and 114 mA/mm for the device on SiC.

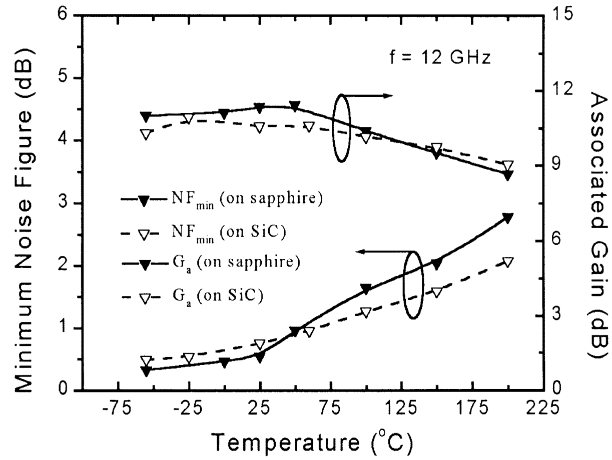

Fig. 9. Minimum noise figure (NF_{min}) and associated power gain (G_a) against measuring temperature of devices on sapphire (solid symbols) and on SiC (open symbols) at 12 GHz. The devices on sapphire were biased at $V_{ds} = 4$ V and $I_{ds} = 40$ mA/mm, while the devices on SiC were biased at $V_{ds} = 10$ V and $I_{ds} = 100$ mA/mm.

with an increase in drain bias to 15 V and, hence, with the dc output power. Also, after G_a rose to the peak value (12.05 dB) at $V_{ds} = 5$ V, it decreased linearly to 7.56 dB with an increase in drain bias. However, for the device on SiC, it was found that the slope of the dependence of drain biases is relatively flat within the measured range. This indicates that AlGaN/GaN HEMTs on SiC have better robustness on microwave noise performance. Though the robustness of the device on the sapphire substrate is not as good as that of devices on SiC, it still exhibited an NF_{min} of 2.14 dB and a G_a of 7.56 dB at $V_{ds} = 15$ V. These noise performances of our AlGaN/GaN HEMTs are comparable with those of GaAs-based HEMTs [12] and MESFETs [13], but with much better robustness since these devices can be biased at high biases and still exhibited respectable noise figures.

Fig. 9 shows the NF_{min} and G_a against measuring temperature of devices on sapphire (solid symbols) and on SiC (open symbols), respectively, where these parameters were measured at a frequency of 12 GHz. In the measurements, the probes and stage of the Microtech probe station were housed in an enclosure that was purged with nitrogen. The stage temperature was controlled by a Temptronic temperature-control system. The devices on sapphire were biased at $V_{ds} = 4$ V and $I_{ds} = 40$ mA/mm, while the devices on SiC were biased at $V_{ds} = 10$ V and $I_{ds} = 100$ mA/mm. Though the drain bias and drain current for the devices on sapphire were kept lower, it was observed that the NF_{min} and G_a of devices had stronger dependence on temperature than that of the devices on SiC. The NF_{min} increased from 0.32 dB at -55 °C to 2.78 dB at 200 °C for the device on sapphire. For the device on SiC, the NF_{min} increased from 0.49 dB at -55 °C to 2.08 dB at 200 °C. A transition temperature was observed to be 25 °C. Above this temperature, the NF_{min} for devices on sapphire increased dramatically in comparison with the situation below this temperature and also in comparison with devices on SiC. It can be concluded that the dependence of NF_{min} on temperature for devices on sapphire is mainly due to the scattering of electrons by polar optical phonons for temperatures below 25 °C. For temperatures above 25 °C, the dependence is a result of the combination of self-heating and electron scattering effects. For the devices on SiC, the increase in NF_{min} with temperature is mainly attributed to the scattering of electrons by polar phonons.

V. Conclusion

We have presented the fabrication and characterization of AlGaN/GaN HEMTs with a gate length of 0.18 μm on sapphire substrates. The devices exhibited a high current drive capability of 920 mA/mm and a peak extrinsic transconductance of 212 mS/mm. A record high f_T of 100 GHz and an f_{MAX} of 140 GHz were obtained for GaN FETs on sapphire substrates. The microwave noise characteristics of these devices were characterized. At the drain bias of 4 V and the drain-current bias of 39.4 mA/mm, the devices exhibited an NF_{min} of 0.48 dB and a G_a of 11.16 dB at 12 GHz. The NF_{min} and G_a values were 1.1 and 9 dB at 18 GHz, respectively. The noise performance dependences on drain bias and drain current were also characterized. With the drain bias fixed at 4 V, the peak G_a and lowest NF_{min} were measured at $I_{ds} = 60$ and 40 mA/mm, respectively. These values are lower than the drain-current values of peak G_a and lowest NF_{min} in comparison with devices on SiC. With the drain current fixed at 40 mA/mm, the NF_{min} increased almost linearly with increase in drain bias, from 0.54 dB at $V_{ds} = 4$ V to 2.14 dB at $V_{ds} = 15$ V. However, the NF_{min} and G_a of devices on SiC were relatively independent of drain biases, indicating a better robustness on microwave noise performance, which is attributed to the excellent thermal conductivity of SiC substrates. The high-frequency noise characteristics against temperature were investigated. Though the drain bias and drain current for the devices on sapphire were kept lower, the NF_{min} and G_a values had stronger dependence on temperature than those of devices on SiC. At $V_{ds} = 4$ V and $I_{ds} = 40$ mA/mm, the NF_{min} at 12 GHz increased from 0.32 dB at -55 °C to 2.78 dB at 200 °C. To our knowledge, the above results are the best microwave noise performance for GaN FETs on sapphire substrates ever reported. This is attributed to the high quality of the AlGaN/GaN epilayer and the optimized fabrication process. These excellent performances indicate the robust low-noise application potentials of AlGaN/GaN HEMTs in X- and Ku-band microwave frequency ranges. With the combined maturity of nitride-based growth techniques and further optimization of process technologies, it is expected that even better device performances will be obtained in the near future.

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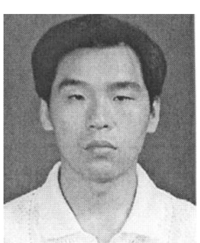

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